

Improved Interpretation of Water Content Reflectometer Measurements in Soils

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ABSTRACT

Water content reflectometers use time domain reflectometry (TDR) to estimate the apparent permittivity of soil, which in turn can be related to the soil water content. The objective of this study is to develop a physical model for water content reflectometers. The length of the sensor rods and the delay time of the circuitry in the probe head are the two unknown parameters. The two parameters are determined both analytically, using sensor readings in air and deionized water, and by optimization, using air and non-conductive fluids. The calibrated parameters are used to calculate the apparent permittivity as a function of water content for sensor readings in five soils, ranging from sand to silt loam. Calculated permittivity values are compared with Topp's permittivity-water content relationship. Results show that the calculated permittivity values for the sand compare reasonably well with Topp's equation. The permittivity in the sandy loam to silt loam soils is overestimated by as much as 104 dimensionless permittivity units. The overestimated permittivity values are due to dielectric dispersion and ionic conductivity, brought about by the low effective frequency in the electromagnetic pulse of the sensors as compared with standard TDR. The performance of the reflectometers may be improved by increasing the frequency of operation of the sensors from <175 MHz to >1 GHz. At higher frequencies, the sensors become less sensitive to ionic conductivity. Furthermore, dielectric dispersion becomes less of an issue at higher frequencies, thereby increasing the applicability of existing permittivity-water content relationships such as Topp's equation.

SOIL WATER CONTENT is an important factor in many plant-soil-water studies and larger scale hydrological investigations. Estimation of soil water content, therefore, is receiving a lot of attention (Dane and Topp, 2002, p. 417–1074). In the field, three methods are available: gravimetric techniques, nuclear techniques (e.g., neutron scattering), and electromagnetic techniques. Of these, electromagnetic techniques have become popular because they facilitate a rapid, safe, nondestructive, and easily automated estimation of soil water content.

Among the electromagnetic techniques, TDR is widely used in research (e.g., Noborio, 2001; Jones et al., 2002; Robinson et al., 2003). The availability of an empirical relationship between permittivity and water content that performs well for many TDR measurements in mineral soils (Topp et al., 1980) initiated its wide adoption. The ability to measure both water content and bulk electrical

conductivity (EC) in the same soil volume (e.g., Dalton et al., 1984; Nadler et al., 1991; Castiglione and Shouse, 2003) also contributed to the attractiveness of TDR.

The relatively high cost of TDR, brought about by the need for a separate pulse and sampling unit, has limited its use for routine monitoring purposes. In response, cheaper electromagnetic sensors have been developed such as capacitance sensors (e.g., Dean et al., 1987; Paltineanu and Starr, 1997; Kelleners et al., 2004), impedance sensors (Hilhorst et al., 1993; Gaskin and Miller, 1996; Hilhorst, 2000; Seyfried and Murdock, 2004), and transmission line oscillators (Campbell and Anderson, 1998).

Of these, transmission line oscillators are particularly interesting because they operate in the time domain, like TDR, but do not require a separate pulse and sampling unit. Transmission line oscillators generate consecutive voltage pulses from inside the probe head whereby the arrival of the reflected pulse triggers the next pulse. The output is a square wave with a frequency that is proportional to the number of reflections per second. These sensors can be read directly by a datalogger, resulting in a low price per unit. Transmission line oscillators cannot be used to measure bulk EC as no waveforms are collected.

Transmission line oscillators are marketed as the CS615 (retired model) and CS616 (new model) water content reflectometers (Campbell Scientific Inc., Logan, UT). Seyfried and Murdock (2001) tested six CS615s in the laboratory and found that separate calibration equations were required to accurately predict the water content in four different soils. Sensor to sensor variability was found to be significant, and variations in temperature influenced the sensor response. The effect of bulk EC on the sensors was not tested separately but was assumed to be strong. The need for a soil specific calibration, and the need to account for the variability among sensors, was confirmed by Chandler et al. (2004) who calibrated CS615s in the field against conventional TDR measurements.

In this work, the data of Seyfried and Murdock (2001) are reexamined, together with more recent data obtained with a CS616 (Blonquist et al., 2005). A physical framework is presented that relates the sensor output to the apparent permittivity. The relationship between apparent permittivity and soil water content is treated separately. This two-step approach facilitates a more rigorous investigation into the performance of the sensors. The specific objectives are (i) to present a simple physical calibration approach for the determination of apparent permittivity from the sensor output, (ii) to quantify the effect of dielectric dispersion and bulk EC on the sensor output in soils, and (iii) to comment on

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Abbreviations: EC, electrical conductivity; EC_s, electrical conductivity of the saturated paste extract; TDR, time domain reflectometry.

the optimum frequency characteristics of the voltage pulse for these sensors.

THEORY

Time Domain Reflectometry

Time domain reflectometry measures the travel time of a step voltage pulse along a transmission line. In soil science applications, the transmission line generally consists of two or more metal rods embedded in the soil. The travel time t (T) of the voltage pulse can be related to the relative real permittivity ϵ_r' (-) and the relative apparent permittivity ϵ_a (-) of nonmagnetic soil through (Von Hippel, 1954; Topp et al., 1980):

$$t = \frac{2L}{c} \sqrt{\frac{\epsilon_r'}{2} [1 + (1 + \tan^2 \delta)^{0.5}]} = \frac{2L\sqrt{\epsilon_a}}{c} \quad [1]$$

where L is the length (L) of the rods, c is the velocity ($L T^{-1}$) of light in vacuum ($= 2.9979 \times 10^8 \text{ m s}^{-1}$), and $\tan \delta$ is the loss tangent (-). The factor two is included in Eq. [1] to account for the fact that the reflection of the pulse has to travel back along the rods before it is detected. The loss tangent is defined as (Topp et al., 2000):

$$\tan \delta = \frac{\epsilon_r''}{\epsilon_r'} = \frac{\sigma/\omega\epsilon_0 + \epsilon_{r,rel}''}{\epsilon_r'} \quad [2]$$

where ϵ_r'' is the relative imaginary permittivity (-), σ is the dc ionic conductivity ($L^{-3} T^3 M^{-1} I^2$), ω (T^{-1}) is the angular frequency ($= 2\pi F$, with $F [T^{-1}]$ being the frequency), ϵ_0 is the permittivity in vacuum ($L^{-3} T^4 M^{-1} I^2$) ($= 8.8542 \times 10^{-12} \text{ F m}^{-1}$), and $\epsilon_{r,rel}''$ is the loss (-) due to dielectric relaxation. Note that ϵ_a in Eq. [1] $\approx \epsilon_r'$ if $\tan \delta \ll 1$.

The CS615 and CS616 reflectometers measure the number of reflections per second. The number of reflections is divided by a scaling factor S_f (-) to facilitate recording by a datalogger. The output is generally read as a period $P(T)$, which is inversely related to the number of reflections per second. The travel time t for the reflectometers is (Campbell and Anderson, 1998):

$$t = \frac{2}{f_r} = \frac{P}{S_f} = \frac{4L\sqrt{\epsilon_a}}{c} + 2t_d \quad [3]$$

where f_r is the number of reflections per second (T^{-1}) before scaling, and t_d is the delay time (T) in the probe head before the next pulse is triggered. This time delay includes detection circuit delay, amplifier delay, and circuit board delay. The factors four and two in Eq. [3] are included because one full cycle involves two voltage pulses. The first voltage pulse (travel distance $2L$, delay time t_d) switches the amplifier from a high voltage level to a low voltage level. The second voltage pulse (again with travel distance $2L$ and delay time t_d) switches the amplifier from the low voltage level back to the high voltage level.

The scaling factor for the CS615s is 32 768, while the scaling factor for the CS616s is 1024. Another important difference between the two sensors is the rise time t_r (T) of the voltage pulse which is about 8 ns for the CS615 and about 2 ns for the CS616. The rise time of the voltage pulse can be related to the maximum frequency F_m (T^{-1}) in the incident electromagnetic wave through (e.g., Bogart et al., 2004):

$$F_m = \frac{\ln(0.9/0.1)}{2\pi t_r} \quad [4]$$

This equation is used in electrical engineering to describe the

frequency characteristics of a low-pass filter. It is only accurate when the energy contained in the voltage pulse is equally distributed across the frequency bandwidth, which is not necessarily true for the CS615 and CS616. The resulting F_m values of 44 MHz (CS615) and 175 MHz (CS616) should therefore be treated as approximations. Note that these F_m values refer to the input signal. The highest frequencies in the reflected signal are lower and depend on the circuitry in the probe head, the quality of the connection between the circuit board and the rods, the rod length, and the dielectric properties of the soil. The longer the rods, and the higher the dielectric loss in the soil, the more the voltage pulse will become attenuated, with the higher frequencies (highest attenuation constant, lowest power) disappearing first (e.g., Yanuka et al., 1988; Friel and Or, 1999).

Water Content-Permittivity Relationship

Several physical and empirical models exist to relate the permittivity of soil to its volumetric water content θ (-). The empirical equation of Topp et al. (1980) generally performs well for TDR measurements in coarse-grained mineral soils:

$$\theta = -5.3 \times 10^{-2} + 2.92 \times 10^{-2} \epsilon_a - 5.5 \times 10^{-4} \epsilon_a^2 + 4.3 \times 10^{-6} \epsilon_a^3 \quad [5]$$

The water content-permittivity relationship can also be described by a semi-theoretical linear equation (e.g., Ledieu et al., 1986; Herkelrath et al., 1991; Heimovaara, 1993):

$$\theta = a_1 \sqrt{\epsilon_a} + b_1 \quad [6]$$

This equation is often called the refractive index model. With $a_1 = 0.115$ and $b_1 = -0.176$, θ according to Eq. [6] deviates $< 0.01 \text{ m}^3 \text{ m}^{-3}$ from θ according to Eq. [5], for $0.05 < \theta < 0.45$ (Topp and Reynolds, 1998).

MATERIALS AND METHODS

Both the CS615 sensor and the CS616 sensor consist of two parallel metal rods that serve as a waveguide and a probe head that contains the circuitry (including the amplifier that generates the voltage pulse). The rods are 30 cm long, have a diameter of 0.32 cm, and have a spacing of 3.2 cm. The probe output (a square wave with frequency $f_r/2S_f$ and period P) can be obtained by connection to a datalogger. For most uses the volumetric water content as calculated by factory or custom calibration equations is obtained directly by programming the datalogger (Campbell Scientific Inc., 1996; Campbell Scientific Inc., 2004). In this study only the measured periods P will be used.

Laboratory measurements with six CS615 sensors were conducted in air ($\epsilon_r' = 1$), ethanol (static $\epsilon_r' \approx 24.3$, according to Weast [1985]), and deionized water (static $\epsilon_r' \approx 80$, depending on temperature). The fluid experiments were performed in 33-cm high polyvinyl chloride columns with 10.2-cm i.d. The air and fluid data are particularly useful for sensor calibration because of the non-conductive nature of the media. Furthermore, the relaxation frequencies of ethanol and water of 1 and 17 GHz, respectively are well above the frequency bandwidth of the sensors. The use of air and fluids also eliminates contact problems with the sensor rods as might occur in soils.

The same six sensors were also used to take measurements in four different soil materials at water contents ranging from oven dry to field capacity (again in the laboratory). The four soil materials were construction sand, Lolalita sandy loam (coarse-loamy, mixed, nonacid, mesic Xeric Torriorthent), Searla loam (loamy skeletal, mixed, frigid Calcic Argixeroll), and Larimer loam (fine-loamy over sandy or sandy-skeletal,

mixed, active, mesic Ustic Haplargid). The dry soil materials were mixed with different amounts of deionized water and packed in the same type of columns as used for the fluids. The actual water content and dry bulk density of the soils in the columns were determined by weighing and oven drying. More details about the soils and the experimental procedure can be found in Seyfried and Murdock (2001). In this study we only consider data that were taken at room temperature (20–25°C).

Originally, only one CS616 sensor was examined. Laboratory measurements were conducted in air, deionized water, 2-isopropoxyethanol (static $\epsilon'_r \approx 12.7$), and ten mixtures of deionized water and 2-isopropoxyethanol. The fluid measurements were performed in a glass container (height 39 cm, width 11 and 17 cm). The real and imaginary permittivity of the fluids as a function of frequency were measured with a Hewlett-Packard 8752C network analyzer and a Hewlett-Packard 85070B dielectric probe (Hewlett-Packard, Palo Alto, CA). The real permittivities measured at 100 MHz were used for comparison with the CS616 output ($F_m = 175$ MHz). The temperature in the laboratory was maintained at 25°C throughout the experiments. The temperature of the fluids was 23.9 to 24.7°C. More details about the laboratory experiment with the CS616 can be found in Blonquist et al. (2005).

The CS616 sensor was also used in a field experiment at the Utah Agricultural Experiment Station Greenville research farm in North Logan, UT. The soil was a Millville silt loam (coarse-silty, carbonatic, mesic Typic Haploxerolls). The sensor was installed horizontally at 10-cm depth in a 1 by 2 m plot which was flood irrigated twice with a 30-d interval and then allowed to dry. Twenty-one soil cores (height 5 cm, diameter 2 cm) were taken from 7.5 to 12.5 cm below the soil surface during the second drying period (30 Aug.–15 Sept. 2004) for soil water content determination. The soil cores were taken outside the range of influence of the sensor to avoid impacting subsequent sensor readings.

Several other types of soil water content sensors were also examined during the field experiment at the Greenville farm. These sensors were also installed horizontally at 10-cm depth. Of these, TDR calculated $\epsilon_a(\theta)$ values and impedance probe calculated $\epsilon'_r(\theta)$ and $\epsilon''(\theta)$ values were selected for comparison with the CS616 calculated $\epsilon_a(\theta)$ values. The TDR data were obtained with a three-rod probe (rod diameter 0.32 cm, length 15 cm, spacing 1.2 cm) connected to a Tektronix 1502B cable tester (Tektronix Inc., Beaverton, OR). The impedance measurements were conducted with a Stevens Hydra probe sensor (Stevens Water Monitoring Systems Inc., Beaverton, OR).

Finally, two more CS616's were examined during this work to verify the laboratory results of Blonquist et al. (2005). The two sensors were used only in air and deionized water. The temperature of the deionized water (22.6–22.7°C) was measured using an Omega HH41 digital thermometer (Omega Engineering Inc., Stamford, CT). The relative real permittivity of the deionized water $\epsilon'_{r,diw}(-)$ was calculated using the following empirical equation (Hasted, 1973):

$$\epsilon'_{r,diw} = 87.74 - 4.0008 \times 10^{-1}T + 9.398 \times 10^{-4}T^2 - 1.41 \times 10^{-6}T^3 \quad [7]$$

where T is the temperature in degrees Celsius. Note that Eq. [7] assumes that the measurement frequency is well below the relaxation frequency of water of 17 GHz. Equation [7] was also used to calculate the permittivity of the deionized water for the CS615 experiments of Seyfried and Murdock (2001).

RESULTS AND DISCUSSION

Sensor Calibration

Equation [3] can be used to calculate the permittivity ϵ_a from the period P if the length L and the delay time t_d are known. The physical length of the rods is about 0.3 m for both the CS615 and the CS616 sensors. However, the true length L as experienced by the voltage pulse will slightly vary. This length can be calculated analytically for each sensor by subtracting Eq. [3] for a measurement in air from Eq. [3] for a measurement in deionized water:

$$\frac{P_{diw}}{S_f} - \frac{P_{air}}{S_f} = \frac{4L\sqrt{\epsilon_{a,diw}}}{c} - \frac{4L\sqrt{\epsilon_{a,air}}}{c} \quad [8]$$

where $\epsilon_{a,diw} = \epsilon'_{r,diw}$ and $\epsilon_{a,air} = \epsilon'_{r,air}$ (zero dielectric loss). The calibrated length now becomes:

$$L = \frac{c(P_{diw} - P_{air})}{4S_f(\sqrt{\epsilon_{a,diw}} - \sqrt{\epsilon_{a,air}})} \quad [9]$$

With L known, t_d can now be calculated from Eq. [3] using either the air or the deionized water measurement. The resulting L and t_d values for all six CS615 sensors and the three CS616 sensors are shown in Table 1 (second and third column).

Alternatively, L and t_d can also be determined by minimizing the sum of squared differences between the observed period and the period according to Eq. [3]. In this way all three (CS615) and all 13 (CS616 of Blonquist et al. [2005]) non-conducting media can be used for sensor calibration. The resulting L and t_d values are also shown in Table 1 (Columns 4 and 5), together with the corresponding R^2 values. The optimized periods and the measured periods are compared in Fig. 1. For the CS615 only the first sensor is shown as the results for the other five sensors were almost the same.

Table 1 shows that there is excellent agreement between calculated and optimized L and t_d values, especially for the six CS615s. The agreement between measured and optimized periods is also good (Fig. 1). The calculated and optimized L values of between 29.42 and 30.08 cm for the six CS615 sensors are all close to the physical length of the rods of 30 cm, as would be expected. The values of t_d for the CS615s are between 8.70 and 9.15 ns, which is above the reported amplifier delay (= rise time t_r) of 8 ns. This indicates that the sum of

Table 1. Calculated and optimized length L and delay time t_d for the CS615 and CS616 water content reflectometers.

Sensors	Calculated		Optimized		R^2
	L	t_d	L	t_d	
	cm	ns	cm	ns	
CS615					
1	29.42	8.87	29.43	8.75	0.999
2	29.76	9.15	29.77	9.03	0.999
3	30.02	9.15	30.03	9.00	0.999
4	30.08	8.90	30.08	8.77	0.999
5	29.87	8.80	29.87	8.70	1.000
6	29.92	9.13	29.92	9.01	0.999
CS616					
1	25.68	5.44	26.31	4.92	0.996
2	26.11	5.53	—	—	—
3	26.24	5.54	—	—	—

the detection circuit delay and the circuit board delay is approximately 1 ns.

The calculated (three) and optimized (one) L values for the three CS616s of 25.68 to 26.31 cm are lower than expected. The reasons for this are not well understood. We speculate that there might be an impedance mismatch between the probe head (low impedance) and the waveguide, which is especially troublesome when measuring in low permittivity media such as air (high impedance). This impedance mismatch may result in a significant portion of the voltage pulse being reflected back to the amplifier from the probe head-waveguide interface. This might result in an early triggering of the next voltage pulse, increasing the number of reflections f_r , and hence result in an underestimation of L (see Eq. [3]). The relatively low L values for the CS616s do not affect the suitability of this sensor for measuring permittivity, or affect the applicability of Eq. [3], since the agreement between measured and optimized periods remains excellent ($R^2 = 0.996$).

In the remainder of this work only the air and deionized water calculated L and t_d values will be used. We recommend using the analytically calculated values because of the simplicity of the methodology, and because no hazardous chemicals are needed for sensor

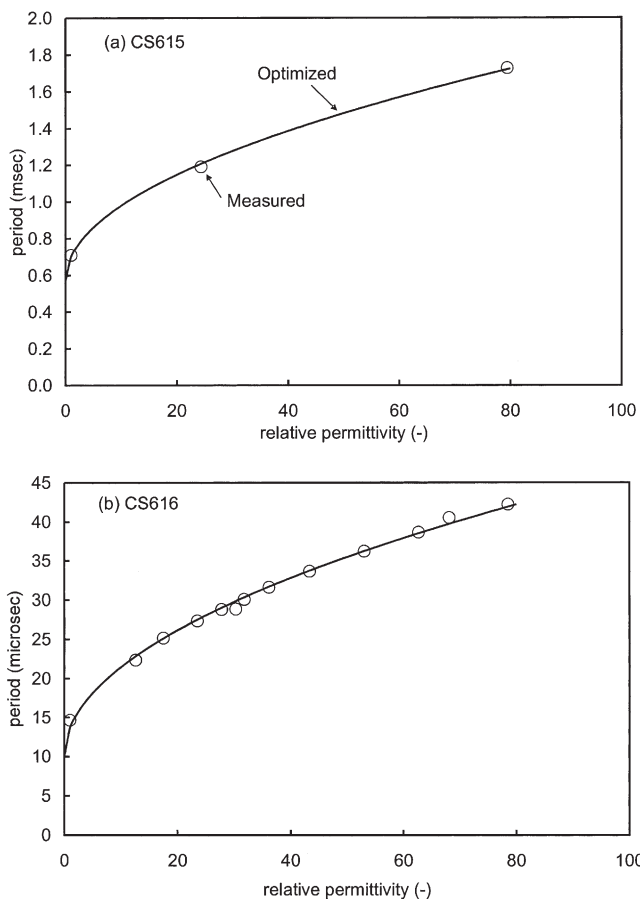


Fig. 1. Measured and optimized sensor period P as a function of the relative permittivity for (a) the first CS615 sensor in air, ethanol, and deionized water and (b) the CS616 sensor in air, 2-isopropoxyethanol, deionized water, and 10 mixtures of deionized water and 2-isopropoxyethanol.

calibration. The proposed calibration procedure can be used to account for sensor to sensor variability, which will be particularly useful for field monitoring studies where multiple sensors are used. The calibration procedure also facilitates the development of sensor-specific relationships between the permittivity and soil water content. This will result in a better understanding of the frequency dependence of the ϵ_a - θ relationship and the detrimental effect of ionic conductivity on the sensor readings.

CS615 in Four Soils

Figure 2 shows the calculated apparent permittivity as a function of water content for the CS615s in all four soils. The apparent permittivity was calculated from the measured period by solving Eq. [3] for ϵ_a . The Topp model (Eq. [5]) serves as a reference. Figure 2 shows that the ϵ_a values for sand follow the model reasonably well, while the Searla loam and Larimer loam show much higher ϵ_a values for $\theta > 0.15$. The Lolalita sandy loam takes an intermediate position. The scatter in some of the data is due to the experimental procedure. For each data point a new column was packed, resulting in small variations in the dry bulk density.

The discrepancy between the calculated and the Topp ϵ_a values is the result of dielectric dispersion (higher permittivity at lower frequency) and ionic conductivity. Dielectric dispersion influences our calculations because the ϵ_a - θ data of Topp et al. (1980) were measured with a TDR system that used a Tektronix S-52 pulse generator (Tektronix Inc., Beaverton, OR) with a rise time of 25 ps. The resulting F_m estimate of 14 GHz for the input signal (Eq. [4]) is much higher than the F_m estimate of 44 MHz for the CS615. In dispersive materials, such as soils containing clay, the lower frequencies for the CS615 will result in a higher apparent permittivity.

Ionic conductivity influences the CS615 in two different ways. First, non-zero EC increases the imaginary part of the permittivity, and hence ϵ_a . This effect is often ignored, but may be non-negligible in wet saline soils

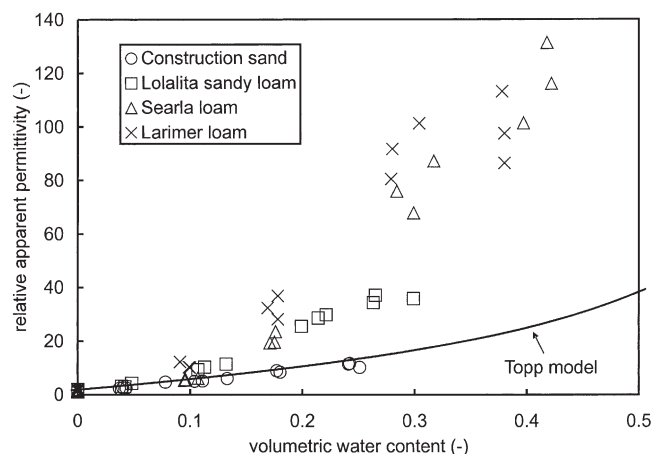


Fig. 2. The calculated relative apparent permittivity ϵ_a as a function of volumetric water content for CS615 sensors in construction sand, Lolalita sandy loam, Searla loam, and Larimer loam. The water content-permittivity relationship according to Topp et al. (1980) is also shown.

with high clay content (Topp et al., 2000). Second, EC increases the attenuation of the voltage of the electromagnetic pulse, and therefore delays the triggering of the next voltage pulse (the input voltage of the amplifier has to cross a threshold). The delayed voltage pulses result in higher P estimates, and, as a consequence, higher ϵ_a values. Thus, ionic conductivity increases ϵ_a both in a direct manner (through the imaginary part), and in an indirect manner (delayed pulses). The low-frequency CS615s are more susceptible to ionic conductivity than high frequency dielectric sensors because the effect of EC on the permittivity decreases with increasing frequency (see Eq. [2]).

The above explains why the match between calculated and Topp ϵ_a values is best for sand (no clay, zero conductivity), intermediate for Lolalita sandy loam (5% clay, electrical conductivity of the saturated paste extract EC_e 2.5 dS m⁻¹), and worst for Searla loam (19% clay, EC_e 7.7 dS m⁻¹) and Larimer loam (29% clay, EC_e 1.5 dS m⁻¹). It's impossible to quantify the relative contributions of dispersion and conductivity to the high ϵ_a values on the basis of the presented data. However, previous high-frequency TDR $\epsilon_a(\theta)$ measurements in the same construction sand, Lolalita sandy loam, and Searla loam (Seyfried and Murdock, 1996) and low-frequency 50 MHz impedance $\epsilon'_i(\theta)$ and $\epsilon''_i(\theta)$ measurements in all four soils (Seyfried and Murdock, 2004) can be used to further interpret the CS615 results.

The 1996 TDR study showed that the measured ϵ_a values for the three sand to loam soils followed Topp's curve closely over the complete water content range. In contrast, the 2004 impedance study showed that only the sand ϵ'_i values followed Topp's curve, while the ϵ''_i values for the sandy loam and loam soils exceeded the Topp ϵ_a values by 3 to 7 dimensionless permittivity units at high θ . Given that $\epsilon'_i(F) \leq \epsilon_a(F)$ (Eq. [1]), the impedance results imply that the sandy loam and loam soils are indeed dispersive (i.e., their permittivity decreases with increasing frequency). However, the magnitude of the dispersion effect seems too small to explain the calculated ϵ_a values of up to 131 units for the CS615s as shown in Fig. 2. This suggests that ionic conductivity is having a major impact on the CS615 readings in the sandy loam and loam soils. The TDR results demonstrate that dispersion and ionic conductivity effects in these soils can be avoided by taking high frequency measurements.

CS616 in a Silt Loam Soil

Figure 3 shows the calculated apparent permittivity as a function of water content for the CS616 in the Millville silt loam. The apparent permittivity is again calculated from the measured period by solving Eq. [3] for ϵ_a . Topp's model serves again as a reference. Tektronix TDR ϵ_a values and Hydra probe ϵ'_i and ϵ_a values are also shown. The Hydra probe ϵ_a values were calculated from ϵ'_i and ϵ''_i by equating the two square root terms in Eq. [1]. Note that some of the scatter in Fig. 3 is due to the experimental procedure where soil samples for water content determination were taken

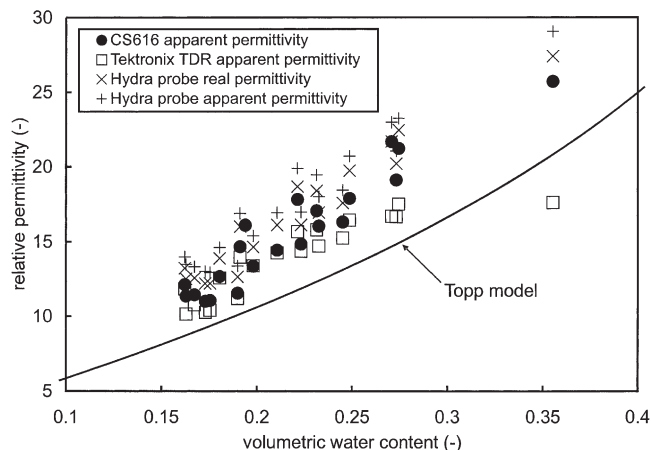


Fig. 3. Calculated relative permittivity as a function of volumetric water content for the CS616 sensor, Tektronix TDR, and Hydra impedance probe in a silt loam soil. The water content-permittivity relationship according to Topp et al. (1980) is also shown.

at some distance from the sensors. Differences in soil temperature over the 17-d measurement period might also have contributed to some of the scatter.

Figure 3 shows that the calculated ϵ_a values for the CS616 exceed the Topp values by 2 to 7 units. The differences for the silt loam soil (15–20% clay; EC_e 0.4 dS m⁻¹) are significantly smaller than the differences between the calculated and Topp ϵ_a values found for the Searla and Larimer loams discussed earlier (Fig. 2). The improved comparison is due to the higher frequency of operation of the CS616 as compared with the CS615, and the low ionic conductivity in the silt loam. Basic differences in dielectric dispersion between the Millville silt loam and the Searla and Larimer loams might again also play a role, despite the small differences in clay percentage.

At most water contents, the ϵ_a values for the different estimation methods in Fig. 3 increase according to $\epsilon_a(\text{Topp}) < \epsilon_a(\text{TDR}) < \epsilon_a(\text{CS616}) < \epsilon_a(\text{Hydra})$. This coincides with a decrease in the (maximum) frequency of the applied electromagnetic field of approximately 14 GHz, 1.75 GHz, 175 MHz, and 50 MHz, respectively (F_m for Topp, TDR, and CS616 estimated from t_r using Eq. [4]). This observation confirms the importance of the measurement frequency, even in a non-saline soil. The difference between the ϵ'_i and the ϵ_a values of up to 1.7 units for the Hydra probe shows that the effect of dielectric loss on ϵ_a is small but not insignificant at 50 MHz.

Sensor Variability and Factory Calibration

Equation [3] can be combined with Topp's model (Eq. [5]) or the refractive index model (Eq. [6]) to relate the measured period P of the reflectometers directly to the water content. Note that insertion of Eq. [6] (solved for $\sqrt{\epsilon_a}$) into Eq. [3] results in a simple linear relationship of the type $\theta = a_2 P + b_2$. For this reason, we preferred to use Eq. [6] (with $a_1 = 0.115$ and $b_1 = -0.176$) instead of Eq. [5]. The resulting P - θ relation-

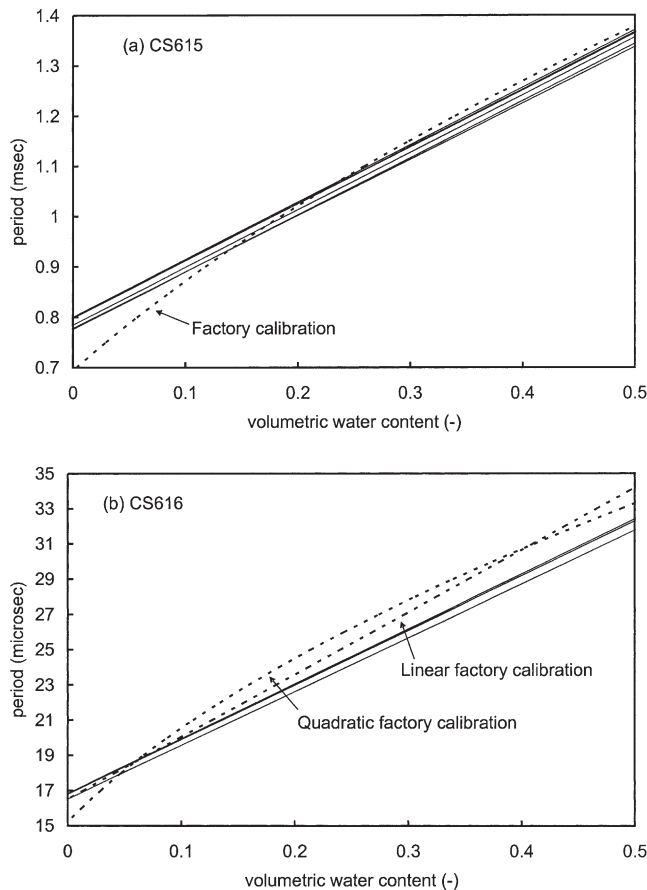


Fig. 4. Calculated period P as a function of water content for (a) the six CS615 sensors and (b) the three CS616 sensors (solid lines), assuming a Topp-like soil with $a_1 = 0.115$ and $b_1 = -0.176$ in Eq. [6]. The water content-period relationships according to the factory calibrations for low-conductivity soils are also shown. Note that some of the solid lines representing the individual sensors almost completely overlap.

ships for all six CS615 and all three CS616 sensors are shown in Fig. 4.

Figure 4 shows that the maximum variation in measured periods for any given water content is about 0.03 ms for the CS615s and about 0.4 μ s for the CS616s. After correction for the difference in scaling factor, this amounts to a maximum variation of 0.9 ns for the CS615 and 0.4 ns for the CS616 (divide by 32 768 and 1024, respectively). Figure 4 also shows the factory calibrations for the CS615 and CS616. The factory calibration for low-conductivity soils for the CS615 is given by the following quadratic equation (Campbell Scientific Inc., 1996):

$$\theta = -0.187 + 0.037P + 0.335P^2 \quad [10]$$

where the period is in milliseconds. For the CS616, both a linear and a quadratic factory calibration are given (Campbell Scientific Inc., 2004):

$$\theta = -0.4677 + 0.0283P \quad [11]$$

$$\theta = -0.0663 - 0.0063P + 0.0007P^2 \quad [12]$$

where the period is in microseconds. The factory calibration for the CS615 compares reasonably well with the sensor curves (Fig. 4a). This is not surprising, as both

the sensor curves (Eq. [3] and [6] combined) and the factory calibration (Eq. [10]) are based on the assumption of a non-dispersive and non-conductive soil. The comparison indicates that the factory calibration equation becomes inaccurate at low water contents ($\theta < 0.1$).

The linear and quadratic factory calibrations for the CS616 (Eq. [11] and [12]) do not compare well with the sensor curves (Fig. 4b). This is probably due to the use of a loam soil (8–26% clay; EC_e about 2 dS m⁻¹) to obtain the factory calibrations for the CS616 (Campbell Scientific Inc., 2004). It can be expected that a true non-dispersive, non-conductive material like sand mixed with deionized water will yield CS616 θ - P data points that are below the factory calibration curves.

Implications

The results of this study show that the water content reflectometers can be calibrated accurately using sensor readings in air and deionized water. This is an appealing method to correct for variability between sensors. The calibrated L and t_d values can be used in Eq. [3] to accurately calculate the apparent permittivity for non-conductive soils. Subsequently, Topp's equation (for non-dispersive soil) or a custom calibration equation (for dispersive soil) can be used to relate the apparent permittivity to the water content. This procedure cannot be applied to conductive soils because of the detrimental effect of conductivity on the period P . Therefore, in saline soils, an empirical P - θ calibration remains the only option.

The effect of ionic conductivity on the observed sensor period reduces with frequency ($\sigma/\omega\epsilon_0$ term in Eq. [2]). Increasing the effective frequency in the electromagnetic signal is therefore beneficial. This can be achieved by selecting a voltage pulse generator with a shorter rise time (see Eq. [4]). Higher effective frequencies also result in smaller differences in dielectric dispersion among soils, thereby increasing the applicability of existing ϵ_a - θ relationships such as Eq. [5], developed by Topp et al. (1980) for high frequency TDR systems. However, the effective frequency cannot be increased too much because it should remain below the relaxation frequency of the soil water.

CONCLUSIONS

Calibration of the physical model for the CS615 water content reflectometers was successful. Calculated L and t_d values based on observations in air and deionized water, and optimized L and t_d values agreed well for all six sensors. The calculated and optimized L values of between 29.42 and 30.08 cm were all close to the physical length of 30 cm of the rods. The calibration for the CS616 sensors was less satisfactory. Calculated (three sensors in air and deionized water) and optimized (one sensor in 13 media) L values of between 25.68 and 26.31 cm were lower than the physical length of 30 cm. We speculated that this unexpected finding for the CS616 is due to an impedance mismatch between the probe head and the rods, resulting in a significant por-

tion of the voltage pulse being reflected back to the amplifier before it enters the rods.

The physical model for the water content reflectometers was used to calculate the apparent permittivity for four soils observed with CS615s. The comparison between calculated ϵ_a and Topp ϵ_a was good for sand, intermediate for sandy loam, and poor for the two loam soils. The discrepancies for the sandy loam and the two loam soils were attributed to ionic conductivity and dielectric dispersion in these soils. Ionic conductivity increases the observed sensor periods, resulting in an overestimation of the apparent permittivity. Dielectric dispersion also results in overestimated ϵ_a values in the presented approach due to the relatively high permittivities found at the relatively low frequency of operation of the CS615s. For practical purposes, Topp's ϵ_a - θ relationship should only be used for reflectometer data in non-dispersive soils.

The physical model describing the P - ϵ_a relationship was also used to describe CS616 observations in a silt loam soil. The low ionic conductivity in this soil, combined with the relatively high frequency of operation of the CS616 (less dispersion), resulted in a relatively good fit between calculated ϵ_a and Topp ϵ_a values. However, calculated ϵ_a values were still overestimated. The performance of the reflectometers may be improved by further increasing the frequency of operation of the sensors. At higher frequencies, the sensors become less sensitive to ionic conductivity. Furthermore, dielectric dispersion becomes less of an issue at higher frequencies, thereby increasing the applicability of existing ϵ_a - θ relationships such as developed by Topp et al. (1980).

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